Predicting Fractures in Glacially Related Fine-Grained Materials and a Synthetic Soil of Bentonite and Sand using Soil Texture

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Abstract

Scientists and engineers from many disciplines have been studying the formation of fractures in fine-grained natural geologic materials and fill. Naturally occurring fractures in the fine-grained materials can create preferential flow paths, which can allow water to infiltrate quickly, resulting in recharge to underlying aquifers but also allowing contaminants to pass through to aquifers, potentially threatening ground water drinking water sources. They can also create zones of weakness that allow piping in dams and slip zones in fill materials. Glacially related fine-grained materials are widely distributed across the northern hemisphere, including the U.S. states of Minnesota, Wisconsin, Michigan, Iowa, Illinois, Indiana, and Ohio; Canada; and much of Northern Europe. It has been difficult to predict the presence of these fractures. The objective of this research was to analyze soil textures of fractured soils and determine boundary conditions for predicting the likelihood of fractures in similar materials, graphically representing the predictive model on the USDA soil texture ternary diagram. An extensive Midwestern U.S. data set (275 data points) including Ohio, Iowa, Michigan, and Wisconsin soil samples was studied. The texture data of those glacially related fine-grained

materialscontaining fractures indicate that those with less than 79% sand and greater than 6.5% clay can be predicted to support fractures. An auxiliary experiment using bentonite suggests that this predictive model may be applicablebeyond the clay mineralogies common to the U.S. Midwest. This is a promising method of predicting which soil textures are most likely to form fractures, and can be a useful field tool for engineering geologists, soil scientists,and other environmental professionals. It is immediately applicable to the U.S. Midwestern sites, and with additional analyses using other soils, could be used more widely across glaciated North America and Northern Europe.

Keywords:Glacially related fine-grained materials; fractures; preferential flow; contaminant transport; soil texture; predictive model

1. Introduction

For many years scientists and engineers from many disciplines have been studying the formation of fractures in fine-grained natural materials and fill. Fine-grained glacial deposits are prone to fracturing. Glacial deposits—the soil, rocks and other materials left behind by glaciers or by melt water streams derived from glaciers—are widely distributed across glaciated North America (Flint, 1971; Stephenson et al., 1988; Roscoe Moss Company, 1990; Warner and Ayotte, 2014) and Northern and Central Europe (Flint, 1971; Roscoe Moss Company, 1990; Klint et al., 2013). Fine-grained glacial deposits are found as glacial tills or diamictites and quiet water deposits, and they typically consist of clays, silt and finer-grained sands. Coarse-grained glacial deposits typically found in kames, kame terraces, eskers and buried valley outwash deposits consist of boulders, cobbles, pebbles and coarser sand fractions. Fine-grained glacially related materials have been considered to be relatively impermeable and thus were thought to be well suited as materials for siting of landfills, earthen waste storage structures for manure, and hazardous waste storage and disposal facilities. It was thought that they provided a protective layer over more permeable aquifers to prevent transport of contaminants to ground water (Stephenson et al., 1988; Simpkins et al., 2002). However, fractures (Fig. 1) in these glacial deposits have been documented in many Midwest States and Canadian Provinces in North America (Connell, 1984; McKay and Fredericia, 1995; McKay et al., 1998; Brockman and Szabo, 2000; Tornes et al., 2000; Rodvang and Simpkins, 2001; Simpkins et al., 2002; Helmke, 2003; Weatherington-Rice, 2003; Szabo, 2006; Dadfar et al., 2010; Stumpp and Hendry, 2012) and Europe (Fredericia, 1990; Jorgensen et al., 2002; Phillips et al., 2007; Cuthbert et al., 2010; Klint et al., 2013). These fractures were the topic of the 1994 Geological Society of America's Penrose Conference held at Racine, Wisconsin where the fractured shoreline bluffs along Lake Michigan were the subject of field investigations. There are six mechanisms of fracture formation in glacially related materials: desiccation, freeze-thaw, shearing from an overriding ice sheet, stress relief from removal of ice, crustal isostatic rebound, tectonic stresses, and volume change due to geochemical processes (Grisak et al., 1976; Brockman and Szabo, 2000).

Fractures can contribute to several problems in geotechnical and geo-environmental

engineering fields such as failures of dams (Sherard et al., 1963; Weatherington-Rice and Hall, 2006), embankments (Dyer and Coulson, 2003; Utili et al., 2014), landfill liners (Miller et al., 1998; Hewitt and Philip, 1999; Yesiller et al., 2000; Tay et al., 2001), landfill caps (Weatherington-Rice and Hall, 2006), and slopes (Lade, 2010; Zhou et al., 2014). Given these potential problems, geotechnical properties should be considered prior to initiation of construction projects to be built with and/or upon glacial materials including landfills, dams, embankments, waste contaminant structures, and building foundations (Connell, 1984; Allred, 2000).

Fractures can create preferential flow paths, which can allow water to infiltrate quickly (Li and Zang, 2011), resulting in recharge to underlying aquifers (Sharp, 1984; Cey et al., 2006; Cuthbert et al., 2010; Griffiths et al., 2011) but also allowing any associated contaminants to pass through to ground water, potentially threatening public health when that ground water is a source of drinking water. Several researchers have observed the rapid transport of contaminants through fractures in glacially related fine-grained materials (Connell, 1984; Rowe and Booker, 1990; Haefner, 2000; Rodvang and Simpkins, 2001; Helmke, 2003; Helmke et al., 2005; Schilling and Tassier-Surine, 2006; Phillips et al., 2007; Rosenbom et al., 2009; Huang and Goltz, 2015). For example, vertical transport of contaminants through glacial till has been documented in Canada (Harrison et al., 1992; McKay and Fredericia, 1995; Best et al., 2015) and Denmark (Sidle et al., 1998; Jorgensen et al., 2002; Jorgensen et al., 2004; Harrar et al., 2007; Chambon et al., 2011). Lateral transport via fractures to surface water streams has also been reported (McKay et al., 1993; McKay et al., 1998).

The occurrence and nature of fractures are controlled by intrinsic soil properties including particle size distribution (i.e., soil texture) and clay mineralogy. Soil texture is one of the two principal factors controlling the creation and development of fractures in glacially derived materials (Gross and Moran, 1971; Steiger and Holowaychuk, 1971; Connell, 1984; Konen, 1995; Tornes et al., 2000; Kim and Christy, 2006; Dadfar et al., 2010). The results of several investigations showed that fractures were more likely to occur in glacial tills with textures classified as loam, clay loam, silty loam, silty clay loam, silty clay, and clay (Gross and Moran, 1971; Steiger and Holowaychuk, 1971; Connell,

1984; Konen, 1995; Tornes et al., 2000; Kim and Christy, 2006), sandy clay loam (Connell, 1984; Kim, 2007; Kim et al., 2010), and sandy loam (Preston et al., 1997; Kim, 2007; Kim et al., 2010) as defined by the U.S. Department of Agriculture's Natural Resources Conservation Service.

Particle size in soils can be divided into three major size classifications: sand, silt and clay by using one of several different classification systems for describing soil texture including those developed by the U.S. Department of Agriculture (USDA), American Association of State Highway and Transportation Officials (AASHTO), Unified Soil Classification System (USCS) and Wentworth (Gerrard, 2000; Hillel, 2004). These systems cannot be directly translated into each other because of differences in origin and purposes, in physical and chemical measurements, and in the differing organized systematic approaches of each of these soil classification systems (Krasilnikov et al., 2009).

The other principal factor in the occurrence of fractures is clay mineralogy. Some clay minerals can cause shrinking and swelling in soils. Shrink-swell behavior leads to cracking and shifting problems (Reid-Soukup and Ulery, 2002; Krenz et al., 2006) and may cause fracturing in glacial tills and unconsolidated materials. Several researchers (Connell, 1984; Brockman and Szabo, 2000; Tornes et al., 2000) specifically investigated the clay minerals found in fractured glacial tills and other unconsolidated materials. Typically a mixture of non-expandable clays including kaolinite, illite and chlorite with limited amounts of vermiculite have been identified in Ohio (Wilding et al., 1971; Brockman and Szabo, 2000; Fausey et al., 2000; Tornes et al., 2000; Bruno et al., 2006; Szabo, 2006; Kim et al., 2010) and Michigan (Monaghan et al., 1986). The clay minerals in Iowa (Hallberg, 1980) and Wisconsin (Connell, 1984) are illite, chlorite, kaolinite, vermiculite plus some expandable clays (e.g., bentonites) as well. However, these same in-situ clay mineralogy groups of unfractured materials in Wisconsin are found to be fractured in Ohio. Thus, there must be at least one additional variable controlling fracturing in fine-grained materials beyond soil texture and clay mineralogy, and that third variable is yet to be identified. Clay mineralogy changes as location shifts from the Midwest towards the western U.S. because more volcanic ash is present in western glacial tills, which then weather out to the higher shrink-swell expandable clays.

Documenting and testing this shifting clay mineralogy is the focus of this paper. By incorporating data on fractured soils beyond Ohio and adding bentonite data, it is possible to expand the region of North America where the presence of fractured fine-grained glacial deposits can be predicted.

Methods of fracture identification in the field, including the azimuthal resistivity method (Boris and Merriam, 2002), seismic measurement (Bakku, 2015) and borehole excavation (e.g., conventional borehole logs, borehole imagery, borehole radar, and flowmeter) (Haefner, 2000), are expensive and inexact. While predicting fractures can be difficult, determining soil texture is a well-defined and time-tested process (Soil Survey Staff, 1993). The range of particle size distribution in fractured glacial tills was first reported as 28 to 45% sand, 36 to 46% silt, and 18 to 35% clay in northeast Ohio (Gross and Moran, 1971). Soils of western Ohio observed to have fractures contained 2 to 38% sand, 30 to 52% silt, and 17 to 68% clay (Steiger and Holowaychuk, 1971). Tornes et al. (2000) concluded that fractures were more likely to occur in glacial tills containing 10 to 72% clay, 26 to 69% silt and less than 50% sand. Given the lack of a practical field method to predict fracture occurrence, another tool was needed beyond azimuthal resistivity, seismic measurement, borehole excavation, and observation of existing road cuts and stream cuts.

Kim and Christy (2006) described statistical and graphical analyses of soil textural data and presented a preliminary model for predicting fractures in glacially-derived materials based on natural field data collected from historic references that documented fractures in glacially related fine-grained materials in Ohio. They worked closely in conjunction with Ohio soil scientists, many of whom were involved with the soil survey mapping for the whole state of Ohio. Kim and Christy (2006) did not define the absolute fracture-controlling boundaries of clay/sand proportions, only the field-identified boundaries. Extensive laboratory scale desiccation fracturing experiments (Kim, 2007; Kim et al., 2010) were subsequently performed on four sets of soil samples found to be naturally fractured in the field in Ohio (high-lime Wisconsinian-aged glacial till from Erie County, high-lime Wisconsinian-aged loess-capped glacial till from Preble County, high-lime leached Illinoian-aged glacial till from Clermont County and low-lime Wisconsinian-

aged glacial till from Stark County), determining how much sand could be added to these samples while still supporting fracturing, and thus approaching the ability to define the absolute soil texture boundaries for fractures. More than 39 individual samples were tested in triplicate by adding increasing proportions of sand to natural Ohio soils until no fracturing was detected. Table 1 lists the volumes of sand added to each soil sample and whether the resulting mixture exhibited fractures upon desiccation. These laboratory drying tests were later replicated with bentonite and sand mixtures to expand our understanding of fracturing boundaries as clay mineralogies change. No combination of bentonite and sand could be found that did not exhibit fracturing. Field data and laboratory data were plotted together on a USDA soil texture ternary diagram to improve the fracturing predictive model using a best-fit method (Kim et al., 2011) which delineated a fracture-prone zone of soils containing less than 79% sand and greater than 6.5% clay, as illustrated in the unshaded area of Figure 2. Because Ohio's kaolinitic clays are not as readily fractured as smectites (Boivin et al., 2004), it is considered likely that this laboratory fracturing research can be applied beyond Ohio.

The hypothesis of this present study was that the fracture-prone soil zone illustrated in a USDA soil texture ternary diagram which had been initially established based on Ohio data (Kim and Christy, 2006; Kim, 2007; Kim et al., 2010; Kim et al., 2011) would be further validated and improved by analyzing a more extensive Midwestern data set, including data from Iowa, Michigan and Wisconsin. A secondary objective was to explore those portions of the USDA ternary diagram that didn't have soil examples in the Midwestern state studies, particularly those soil textures with very low silt content and soil mineralogies with significant amounts of expandable clays. The results would provide a fracture prediction model with more complete coverage of the full range of soils textures mapped on a USDA soil texture ternary diagram and could be applied to studies of environmental problems related to the breakage and fracturing of expandable clay liners used for water impoundments and waste disposal sites across North America.

2. Materials and methods

The first task was to combine all available soil texture data sets for fractured

Midwestern soils and define the boundary conditions (i.e., fracture-prone zone in the ternary diagram) for fracture propagation, specifically minimum clay content and maximum sand content. The second task was to explore those portions of the USDA ternary diagram that didn't have soil examples in the Midwestern state studies, particularly those soil textures with very low silt content and soil mineralogies with significant amounts of expandable clays. Therefore, an additional laboratory desiccation fracturing experiment was performed on commercially available bentonite (i.e., montmorillonite), which has typical expandable clay characteristics and is a main clay component of Western U.S. soils.

2.1 Data acquisition

2.1.1 Wisconsin soil sample data

Connell (1984) investigated fine-grained till and glacio-lacustrine sediment units near and along Wisconsin's Great Lakes northern and eastern shorelines (Fig.3) for distribution, characteristics, and genesis of joints or fractures. He classified the particle sizes using the Wentworth scale: for example, sand, silt and clay sizes are defined as 2 to 0.063 mm, 0.063 to 0.002 mm and <0.002mm, respectively. These data were used to draw particle size distribution curves, which were then used to determine the proportions of sand (2 to 0.05 mm), silt (0.05 to 0.002 mm) and clay (<0.002 mm), with new class breaks based on the USDA soil texture classification system (Kim, 2007).

2.1.2 Ohio, Iowa, Michigan soil sample data

Four field soil samples were collected from sites observed to be fractured in Clark County, Ohio; Portage County, Ohio; Story County, Iowa; and Barry County, Michigan; the locations are mapped on Figure 3. The soil sample from Clark County, Ohio was obtained from a well-drained site near the proposed Clarkco Solid Waste Landfill. The soil sample from Portage County was collected at Lakeside Sand and Gravel Quarry, and represents another well-drained site in Ohio. The soil sample from Iowa was collected at Whatoff's Borrow pit in Story County, Iowa, on a minor moraine at the edge of the Skunk River valley. The soil sample from western Michigan was taken from a Barry

County gravel pit. The exposure consisted of approximately 2.5 m of compact, homogenous, brown till at the surface, overlaying 10 to 15 m of gravel and sand. The diamict (till) had well developed fractures, some of which were visible in the sample.

To plot the soil texture data on the USDA soil texture ternary diagram, particle size analyses of these soil samples that had been documented to be fractured in the field were performed to determine soil texture based on the USDA size classification system using the pipette method (Soil Survey Staff, 1984) at the Soil Characteristics Laboratory at the School of the Environment and Natural Resources, The Ohio State University, Columbus, Ohio.

2.2 Application of the data to a fracture-prone soil zone in USDA Soil Texture Ternary Diagram

The reclassified soil texture data from field-observed fracturing in Wisconsin (98 data points) were added to the Iowa (1 data point), Michigan (1 data point) and Ohio (2 data points) data. The combined data were analyzed to determine the fracture-prone soil zone by a best-fit method (Kim et al., 2011) and compared to the fracture-prone soil zone developed based on a previous Ohio-only study (Kim et al., 2010) along with additional Ohio data points not included in that original study, giving a total of 275 data points generated among the different studies, including this one.

2.3 Bentonite fracturing experiment

Laboratory-scale desiccation fracturing experiments using bentonite followed the standard protocol developed by Kim et al. (2010). This testing protocol, first developed for Ohio fine-grained glacial deposits, is extensively documented and discussed in Kim (2007) and Kim et al. (2010). The commercial bentonite sample (BIG-HORN® CH 325, Wyo-Ben Inc., Billings, MT) was 90% pure clay and 10% silt based on vendor supplied information. The bentonite was modified by adding predetermined amounts of sand to generate a series of bentonite/sand mixtures of varying soil texture compositions. A commercially available product of pure silica sand (effective size (D_{10}/D_{60}) = 0.16 mm), containing >99.0% crystalline silica, as reported on the material safety data sheet

provided by the company, was used as the mixture supplement. In the case of bentonite, higher volumes of distilled water were required for the 500 g bentonite/sand mixture than the standard protocol of laboratory-scale fracturing experiments. Because the bentonite swelled so much, the 1400 cm³ pan overflowed during the experiment. Therefore, smaller amounts of bentonite/sand mixtures were used to make the bentonite slurries. Two sets of each bentonite/sand mixture were prepared and the quantities of bentonite and distilled water were determined by preliminary experiment. One set required 300 mL distilled water for a total 200 g bentonite/sand mixture. The other set required 800 mL distilled water for a total 500 g bentonite/sand mixture. All bentonite based samples were photo-documented daily until fully dried. Drying periods for each sample depended upon temperature and humidity. Ambient temperature and humidity data were collected daily during the drying process. Onset of fracturing on the sample surface was determined by visual observation. The results were then plotted on a USDA soil texture ternary diagram.

3. Results and discussions

Soil textures, as defined on the modified Wentworth scale, of 98 Wisconsin samples documented to be fractured were transformed into the USDA particle size classification system (Kim, 2007). The Wisconsin texture data (98 data points) of fractured samples from Connell (1984) were plotted on the USDA soil texture ternary diagram, indicated as filled circle points in Figure 4. The ranges of sand, silt and clay proportions in these soil samples were 2 to 53%, 10 to 85% and 7 to 85%, respectively.

The results of particle size analysis for four new field samples from Iowa, Michigan, and Ohio were also plotted on the same USDA soil texture ternary diagram (Fig. 4), indicated by the rectangular symbol for the Iowa sample, triangular symbol for the Michigan sample and diamond symbol for the two Ohio samples. The soil sample from Story County, Iowa, was determined to be 54.5% sand, 32.4% silt, and 13.1% clay, placing it in the sandy loam texture class. The proportions of sand, silt and clay in the soil sample from Barry County, Michigan, were 44.2%, 29.4%, and 26.4%, respectively, placing it on the border of the loam and clay loam texture classes. The soil sample from Clark County, Ohio contained 41.4% sand, 40.7% silt and 17.9% clay indicating a

loam texture, whereas the sample from Portage County, Ohio contained 55.0% sand, 38.2% silt and 6.8% clay consistent with the sandy loam class.

These four soil texture data from fractured field samples from Iowa (1 data point), Michigan (1 data point), and Ohio (2 data points) were added to the reclassified Wisconsin data (98 data points). All 102 new data points were found to be located within the fracture-prone soil zone previously established based on the original 173 Ohio combined field and laboratory data (Kim et al., 2010). All of these samples fell within the range of known fractured fine-grain materials from Ohio documented in Figure 2. A combined set of all 275 total texture data points were plotted on a USDA soil texture ternary diagram (Fig. 5). The particle size proportions observed to sustain fracturing on the combined data set are 0 to 79% sand, 8 to 94% silt, and 6.5 to 92% clay. The sand proportion limit was similar to that previously determined using the original Ohio data (Fig. 2 from Kim et al., 2010). However, the lower limit of silt was decreased to 8%, and the observed upper limit of clay was increased to 92% by adding the Wisconsin data. This upper clay boundary was extended to 100% to be in accordance with information from Connell (1984) and Tornes et al. (2000) that tills mapped into the predominantly clay regions (i.e., up to 100% clay) of the ternary diagram were observed in the field to be fractured. The resultant unshaded fracture-prone area of the diagram shows that materials with less than 79% sand, less than 94% silt, and greater than 6.5% clay are predicted to sustain fracturing. This fracture-prone zone includes clay, loam, clay loam, silty clay loam, silty clay, sandy clay, sandy clay loam and silty loam soils, all of which have been observed to support fracturing in glacially related fine-grained materials in the Midwestern United States.

The laboratory fracturing experiments using pure bentonite and bentonite/sand mixtures resulted in all bentonite-based samples being observed to have fractures after the laboratory tests were performed (Fig. 6). The bentonite, a highly expandable clay, was found to produce fractures regardless of the amount of sand added for the laboratory scale fracturing experiments, corresponding to what was observed by Ghazi (2015) and Alkaya and Esener (2011). They suggested that bentonite/sand mixtures which have 5 to 10% bentonite content would satisfy the limit values needed for constructing the clay core of

an earthen dam and clay liner/barrier materials. Figure 7 shows the textures of the six bentonite/sand mixtures plus the pure bentonite sample. The texture data were scattered on the left side of the ternary diagram, parallel with the clay axis. The data points of bentonite/sand mixtures (Fig.7) were not added to the predictive model data (Fig.5) because the bentonite behaves so differently than the typical Midwestern clay minerals. A separate predictive model needs to be developed for Western glaciated North America.

4. Summary and conclusions

Scientists and engineers from many disciplines have been studying the formation of fractures in fine-grained natural materials and fill. Soil texture data (275 total data points) of glacially related fine-grained soil samples containing observed fractures from Iowa, Michigan, Ohio, and Wisconsin were plotted on the USDA soil texture ternary diagram, indicating that soils with less than 79% sand and greater than 6.5% clay can be predicted to support fractures. It is projected that 100% clay would also sustain fractures. Results from a bentonite experiment suggest that this predictive model may be applicable to soils beyond the clay mineralogies common to the Midwest U.S. Further research is needed on soils with different clay mineralogies.

The predictive technique discussed in this paper is best applied to desiccation fractures, although the physical properties discussed may well help to control the perpetuation of fractures created by other five processes identified by Brockman and Szabo(2000). More research is needed to confirm those relationships.

This is a promising method for predicting which soil textures are most likely to form fractures, and can be a useful field tool for prevention of geo-environmental problems caused by failure of engineered construction activities in fracture-prone areas. These soils can also be expected to fracture when used as fill in the built environment. Soils with fracture-prone textures used in earthwork structures and those sand/bentonite mixtures used as liner/barrier materials in various engineering applications should be carefully evaluated prior to use in earthwork construction and then rigorously maintained over time to prevent failure. For those construction applications where the fine-grained materials are used above the uppermost zone of saturation, it should be assumed that desiccation

fracturing will occur over time. Again, careful monitoring and long-term planning are critical.

Engineers, soil scientists, and geotechnical and geoenvironmental professionals can apply this fracturing predictive model represented as a fracture-prone zone in the USDA soil texture ternary diagram to their own site-specific data to predict where fracturing is most likely to occur. The method is immediately applicable to Midwestern sites and, if calibrated using additional analyses of other soil types, could be applied more widely across glaciated North America and Central and Northern Europe.

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Figure captions.

Fig. 1. Vertical fracturing in glacial till exposure at Grasselle Road stream cut, Battelle Darby Metro Park, Franklin County, Ohio (photo by Ralph Haefner, 2000).

Fig.2. Fracture-prone soil zone for the 173 data points from Ohio field samples (143 points) and laboratory results (30points) (modified from Kimet al., (2010), used with permission). The unshaded area shows the observed fracture-prone soils contained less than 79% sand and greater than 6.5% clay.

Fig.3. Locations of soil samples from Ohio, Iowa, Michigan and Wisconsin. The red cross marks inside circles indicate specific sampling locations. The hatched pattern indicates the unglaciated area. The thick green lines indicate the southern limits of glaciations. (Modified map background from U.S. Geological Survey's Geologic Maps of the United States (King and Beikman, 1974)).

Fig.4. Soil texture data of 102 fractured fine-grained glacial sediments from various locations along Wisconsin's Great Lakes shorelines (data modified from Connell (1984)) and of glacial sediment samples from Iowa, Michigan, and Ohio found to be fractured. The circle, rectangular, triangle, and diamond points indicate samples from Wisconsin, Iowa, Michigan, and Ohio, respectively. The unshaded zone indicating the fracture-prone soil zone shows those soil textures expected to support fracturing (less than 79% sand and greater than 6.5% clay).

Fig.5. Soil texture data for all combined 275 fractured, glacially related fine-grained soil samples from Ohio, Iowa, western Michigan, and Wisconsin. The unshaded zone indicating the Fracture-prone soil zone shows those soil textures expected to support fracturing (less than 79% sand, less than 94% silt, and greater than 6.5% clay).

Fig.6. Triplicate laboratory fracturing experiments for 50 g Bentonite sample combined with 450 g pure silica sand at 19.1 ± 3.2 °C and 46 ± 7 % relative humidity. The total 500 g mixture of contained 90.0 % sand, 1.0 % silt and 9.0 % clay.

Fig. 7. Soil textures that developed fractures during drying tests with bentonite/sand mixtures.

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	1 st Day	5 th Day	13 th Day	34 th Day (Final day)	Result
Sample #1					Volume shrinkage + Crack
Sample #2					Volume shrinkage + Crack
Sample #3					Volume shrinkage + Crack

Fig.6. Triplicate laboratory fracturing experiments for 50 g Bentonite sample combined with 450 g pure silica sand at 19.1 ± 3.2 °C and 46 ± 7 % relative humidity. Triplicate laboratory fracturing experiments for 50 g Bentonite sample combined with 450 g pure silica sand at 19.1 ± 3.2 °C and 46 ± 7 % relative humidity. The total 500 g mixture of contained 90.0 % sand, 1.0 % silt and 9.0 % clay.

Fig.7. Soil textures that developed fractures during laboratory desiccation tests with bentonite/sand mixtures.

Table caption.

Table 1. Laboratory scale desiccation test results on five Ohio soil samples.

Table 1. Laboratory scale desiccation test resultson five Ohio soil samples.

Field soils samples	Amount of pure silica sand added, g	Particle size distribution of mixture after pure silica sand addition, %			Test result
		Sand 2-0.05mm	Silt 0.05-0.002mm	Clay <0.002 mm	
Stark County	0	36.6	52.6	10.5	fractured
	30	40.4	49.4	10.2	fractured
	70	45.5	45.2	9.3	fractured
	110	50.5	41.0	8.5	fractured
	150	55.6	36.8	7.6	fractured
	190	60.7	32.6	6.7	fractured
	220	64.5	29.5	6.0	no fractures
	260	69.6	25.3	5.1	no fractures

Clermont County, Sample A	0	27.5	38.5	34.0	fractured
	100	42.0	30.8	27.2	fractured
	150	49.2	27.0	23.8	fractured
	200	56.5	23.1	20.4	fractured
	250	63.7	19.3	17.0	fractured
	300	71.0	15.4	13.6	fractured
	350	78.3	11.5	10.2	fractured
	400	85.5	7.7	6.8	no fractures
Clermont County,S ample B	0	42.6	45.6	11.8	fractured
	50	48.3	41.1	10.6	fractured
	100	54.1	36.5	9.4	fractured
	150	59.8	31.9	8.3	fractured
	200	65.5	27.4	7.1	fractured
	250	71.3	22.8	5.9	no fractures
	300	77.1	18.2	4.7	no fractures
Erie County	0	21.9	55.7	22.4	fractured
	60	31.3	49.0	19.7	fractured
	120	40.7	42.3	17.0	fractured
	180	50.0	35.7	14.3	fractured
	240	59.4	29.0	11.6	fractured
	270	64.1	25.6	10.3	fractured
	310	70.3	21.2	8.5	fractured
	360	78.1	15.6	6.3	no fractures
	390	82.8	12.3	4.9	no fractures
Preble County Loess Sample	0	4.6	80.1	15.3	fractured
	60	16.1	70.5	13.4	fractured
	120	27.5	60.9	11.6	fractured
	180	38.9	51.3	9.8	fractured
	240	50.4	41.6	8.0	fractured
	300	61.9	32.0	6.1	no fractures
	360	73.3	22.4	4.3	no fractures